Superconducting direct drive generators for large offshore wind turbines

Abrahamsen, Asger Bech; Jensen, Bogi Bech; Polinder, Henrik

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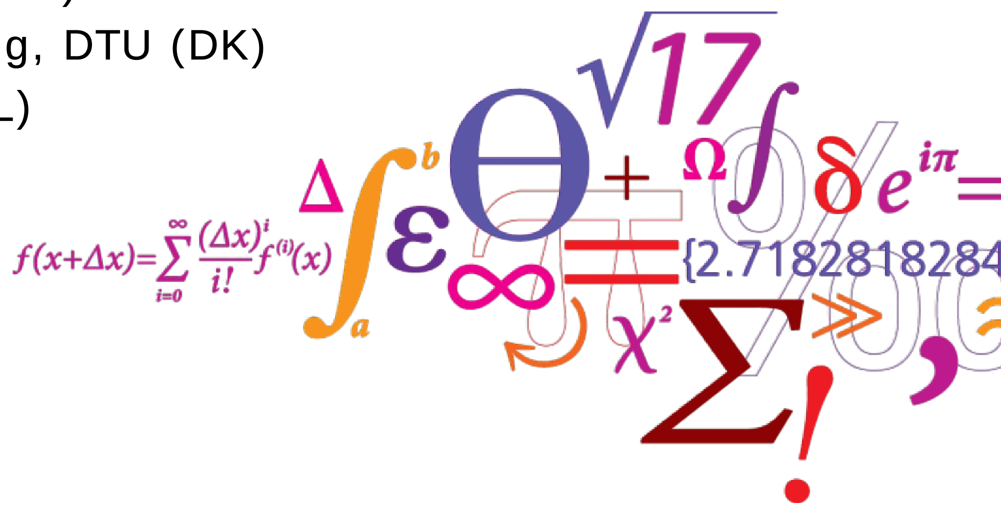
Superconducting direct drive generators for large offshore wind turbines

Asger B. Abrahamsen[1], Bogi Bech Jensen[2] and Henk Polinder[3]

[1]Department of Wind Energy, DTU (DK)
[2]Department of Electrical Engineering, DTU (DK)
[3]Electrical Engineering, TU Delft, (NL)



Battle of the drive trains
EWEA 2013
4 February 2013, Vienna, Austria

Outline

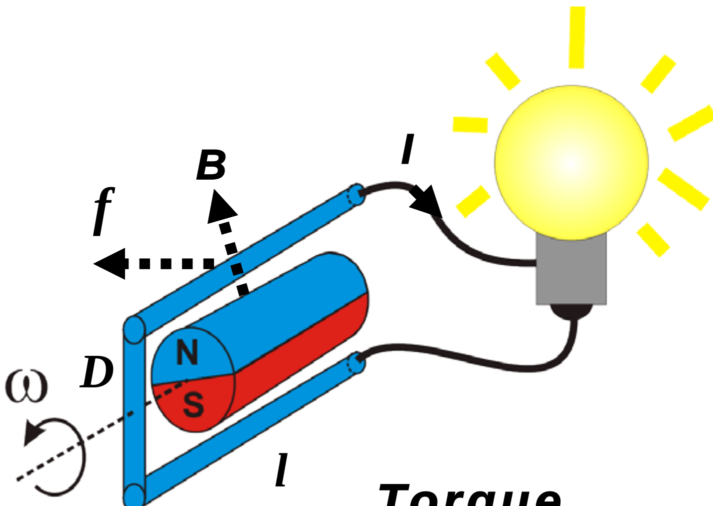
- Motivation : An active material with new properties
- Scaling laws
- Superconducting wires
- Superconducting generators
- CAPEX fraction
- Cooling challenges
- State of the art
- Conclusion

Acknowledgement:

Superwind.dk

INNWIND.EU Work package 3
"Electro- mechanical conversion"

Motivation for superconducting generator

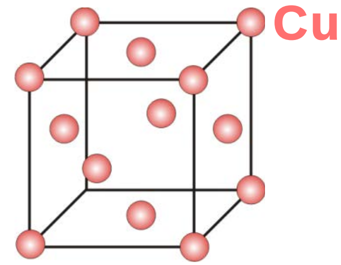


$$Power \propto \overbrace{BI\ D^2 l}^{Torque}\ \omega$$

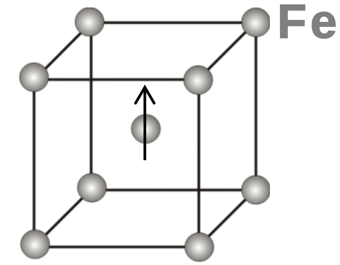
1G : Copper + Iron

2G : $R_2Fe_{14}B$ magnets+Fe
10 MW ~ 6 tons PM

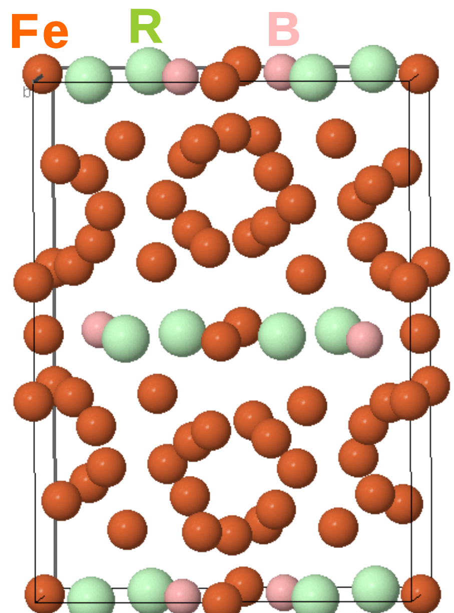
3G : $RBa_2Cu_3O_{6+x}$ HTS + Fe
10 MW ~ 10 kg RBCO



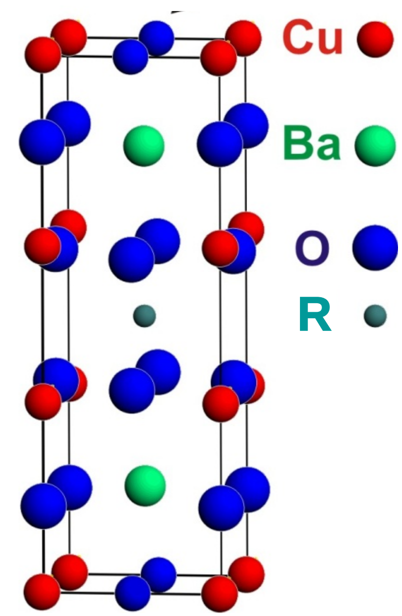
$J \sim 2\ A/mm^2$



$T_C = 1043\ K$
$B_r \sim 0\ Tesla$



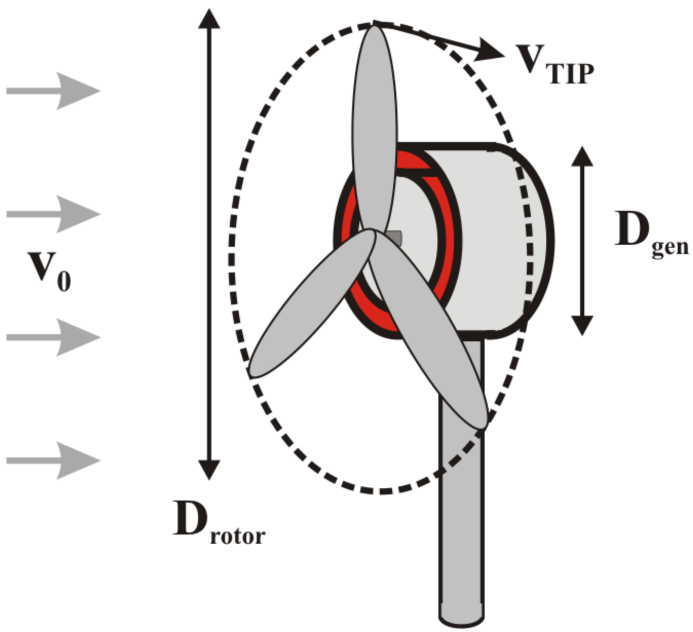
$T_C = 583\ K$
$B_r \sim 1.4\ Tesla$

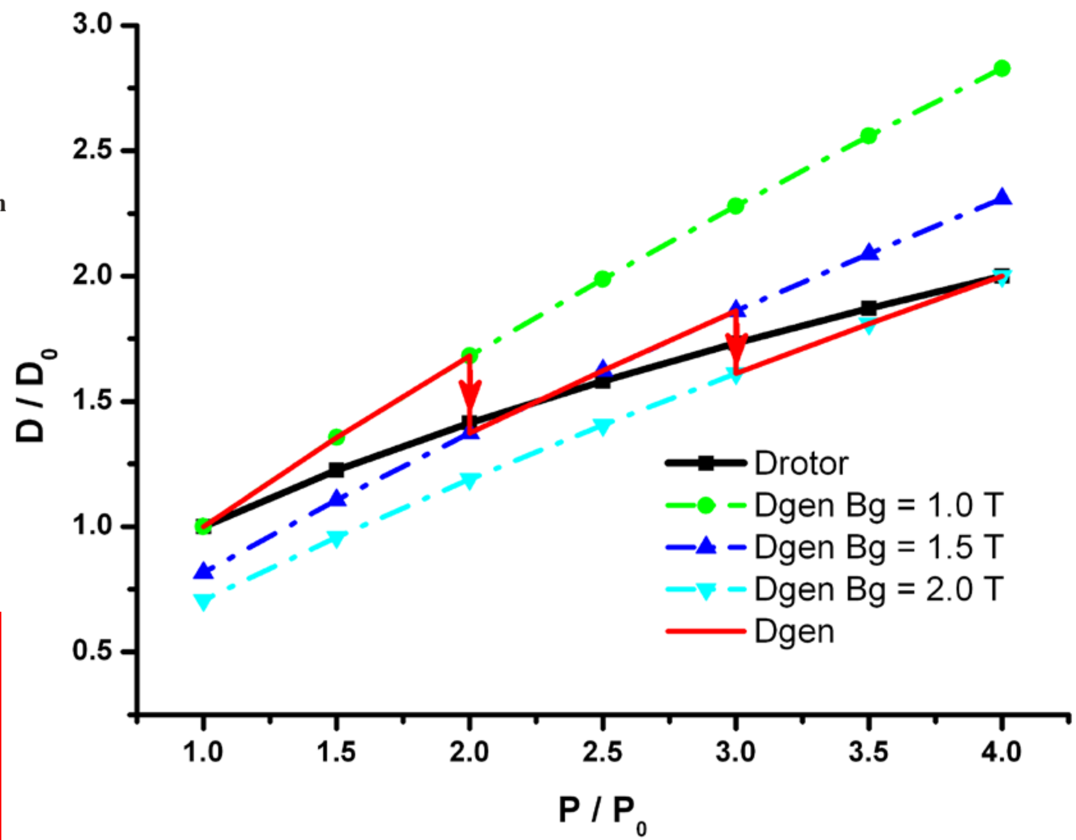


$T_C = 93\ K$
$B_{c2} \sim 100\ Tesla$
$J < 200\ kA/mm^2$

Up-scaling the turbine

Constant tip speed →	**Rotor diameter**	D_{rotor}	$\sim P^{1/2}$
	Torque	T	$\sim P^{3/2}$
	Generator diameter	D_{gen}	$\sim (BI)^{-1/2} P^{3/4}$

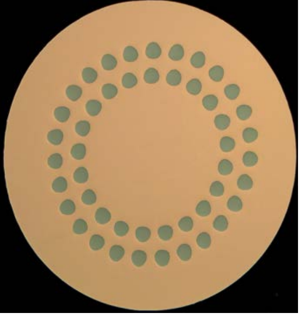




$$
\boxed{\begin{aligned} P = T\omega &= \tfrac{1}{2}\rho D_{rotor}^2 v_0^3 C_p \\ &= B_g I D_{gen}^2 L_{gen}\omega \end{aligned}}
$$

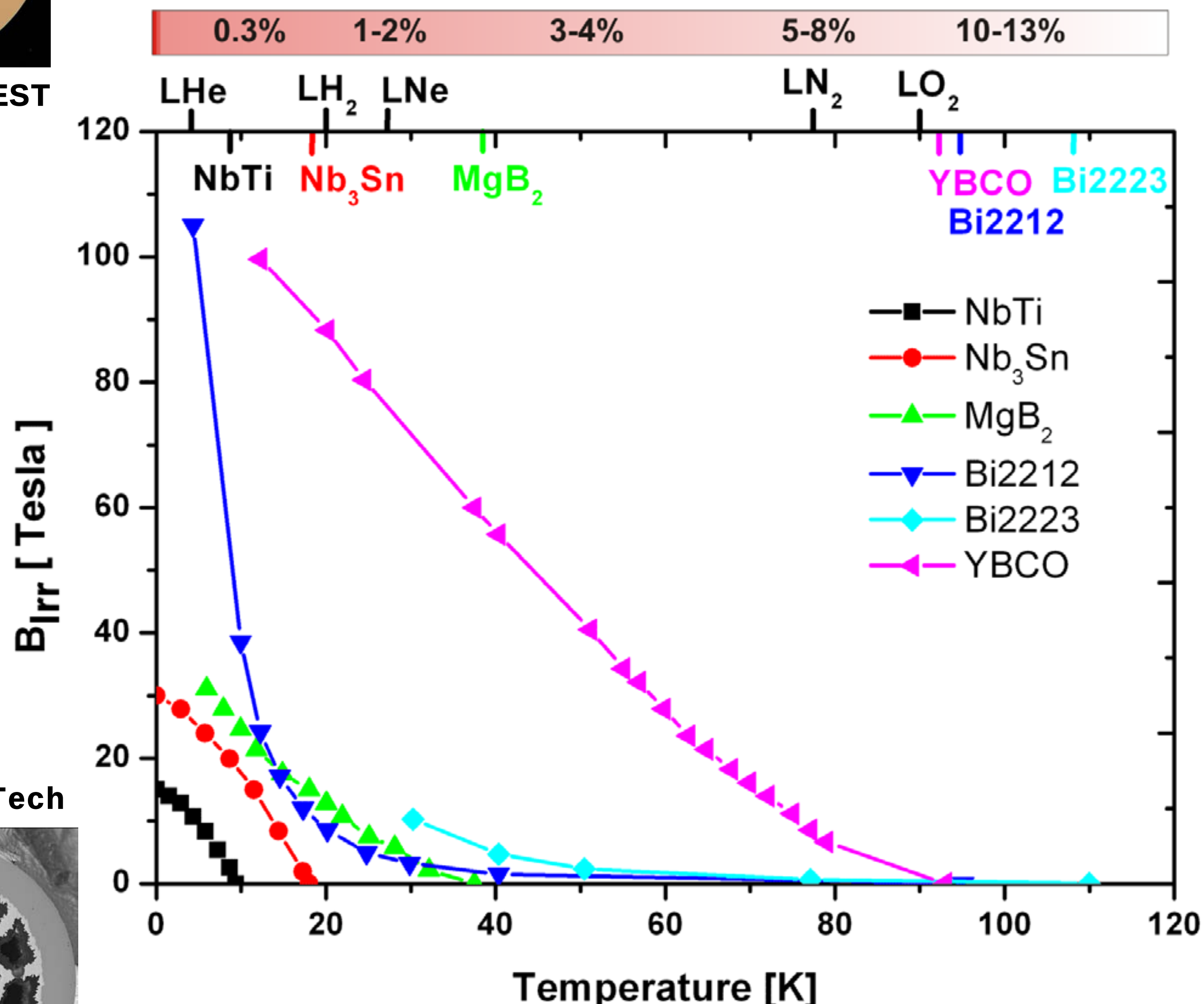
Abrahamsen, Barahona & Jensen, ASC 2012, 4LF-04

Choice of superconductors



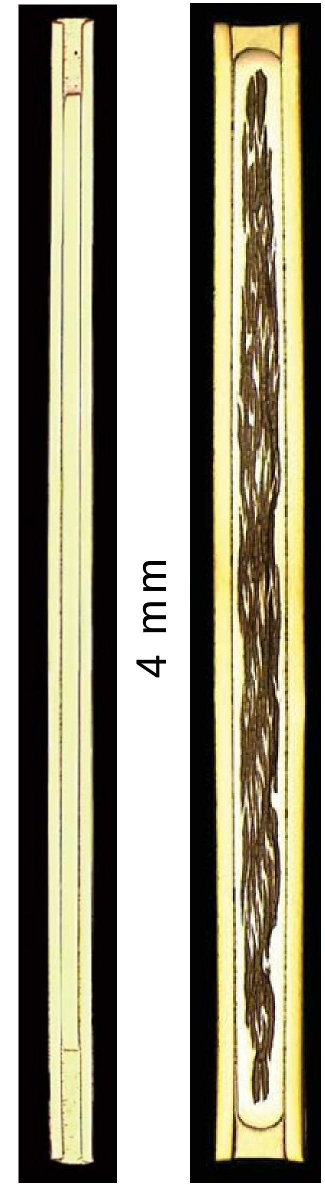
NbTi Bruker EST

0.4 €/m



30 €/m

20 €/m

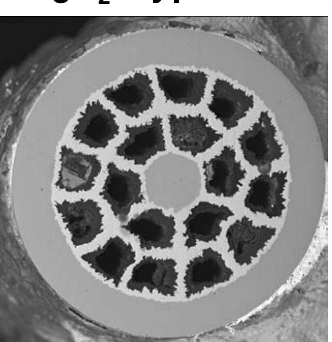


YBCO AmSC

Bi-2223

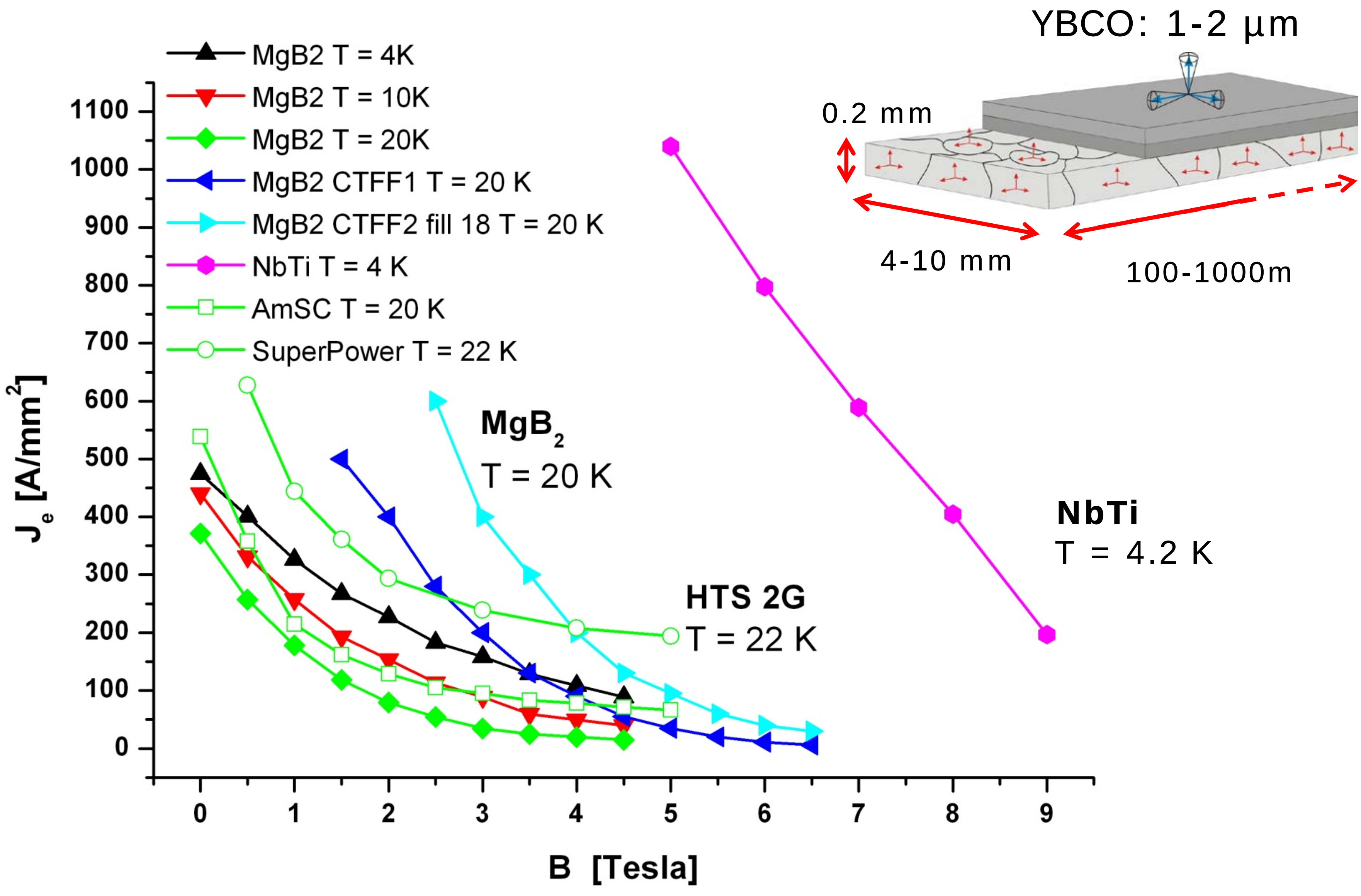
1-4 €/m

MgB_2 HyperTech



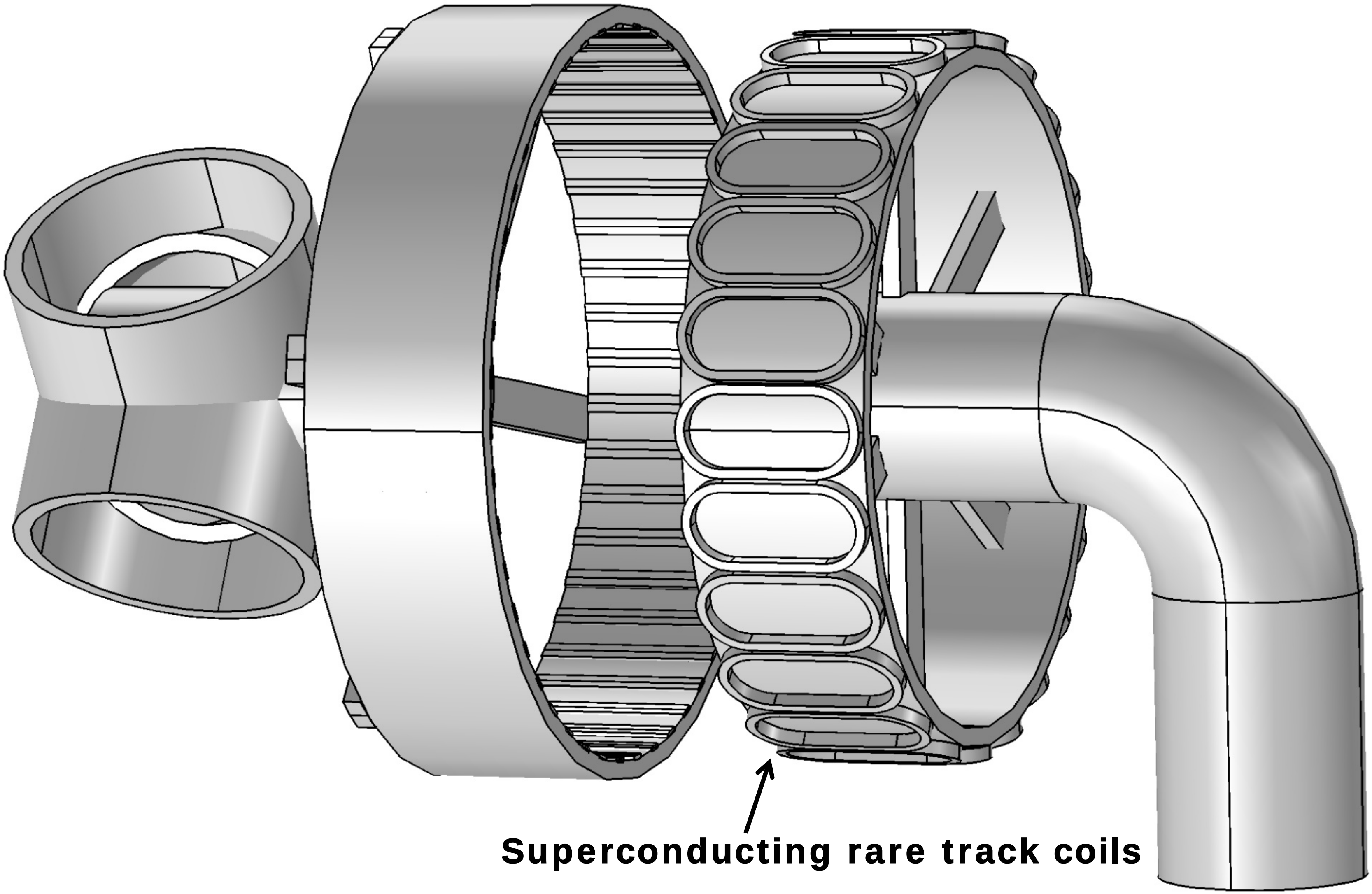
Jensen, Mijatovic & Abrahamsen, EWEA 2012

Engineering critical current $J_e(B,T)$



Topologies

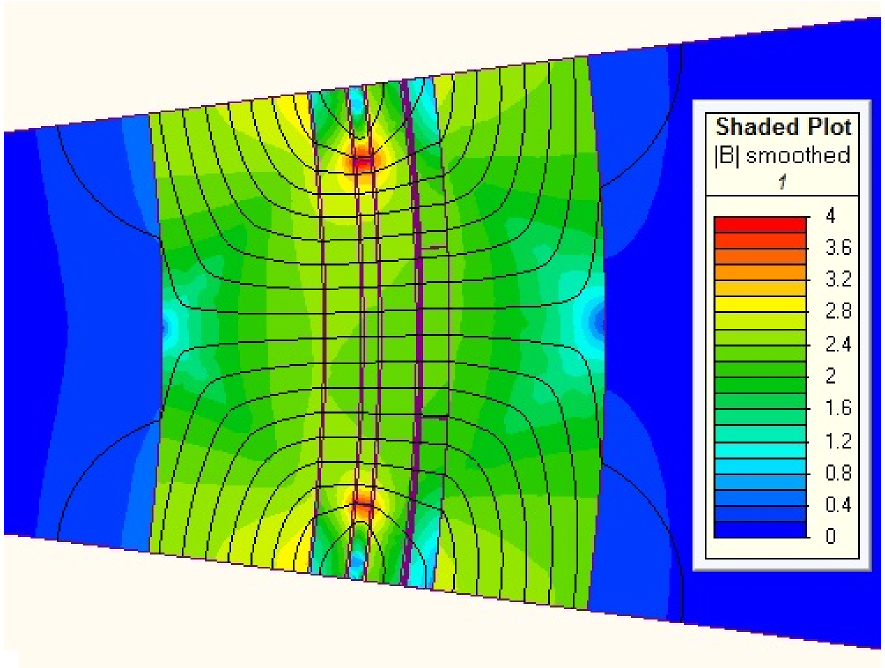
SC coils	Fixed	Rotating
In	☺	☹
Out		



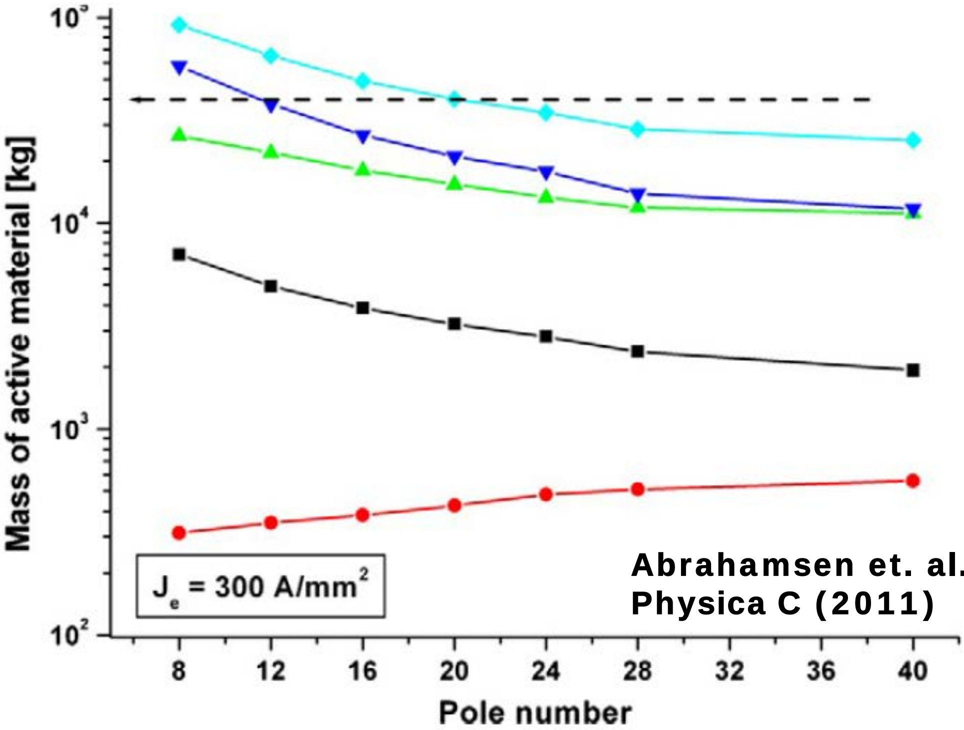
CAPEX fraction

P = 5 MW coated conductor YBCO
D = 4.2 m   L = 1.2 m   24 poles
M_{active} ~ 40 tons

- L_{tape} = 134 km (30 €/m)
- Price ~ 3.9 M€
- CAPEX fraction = 40 % (2 M€/MW)



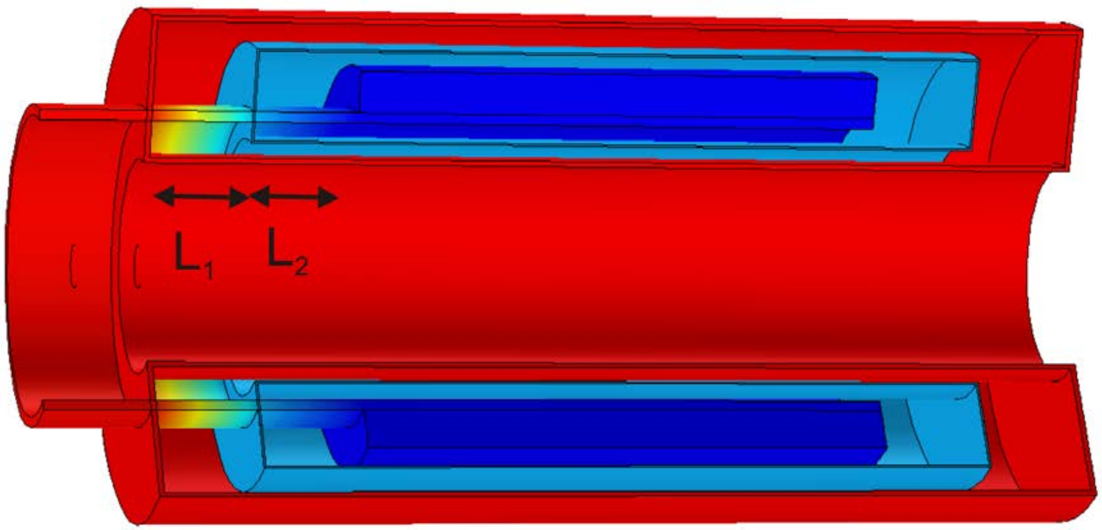
Wire	P MW	L_{wire} km	Wire Price	Capex %
YBCO	5 10	134 357	30 €/m ¤	40 54
MgB_2	5	367	1-3 €/m	4-11
NbTi*	10	720	0.4 €/m	2

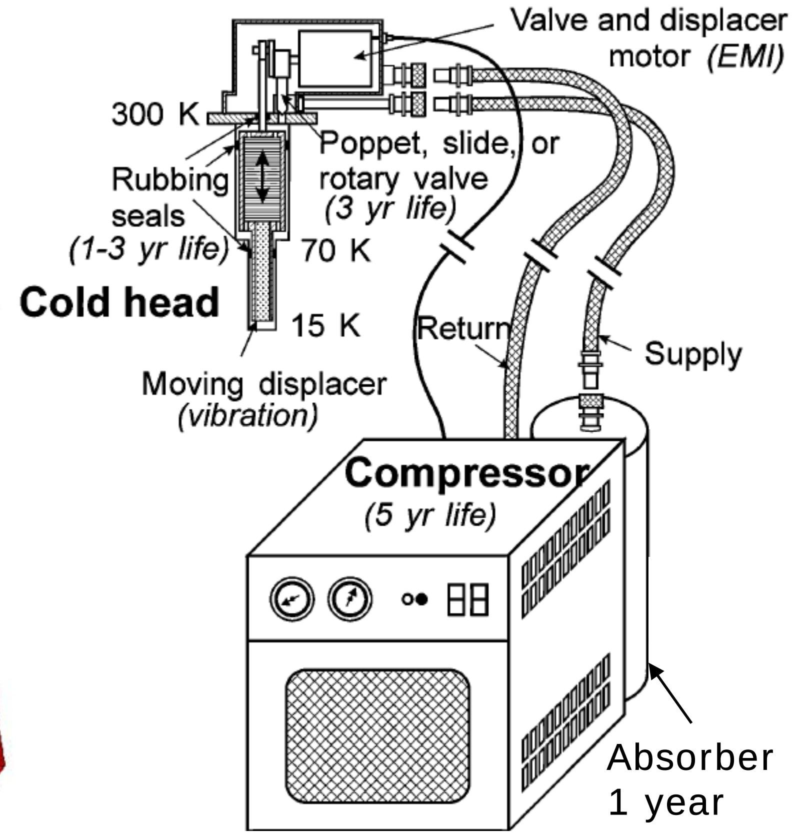


Abrahamsen et. al.
Physica C (2011)

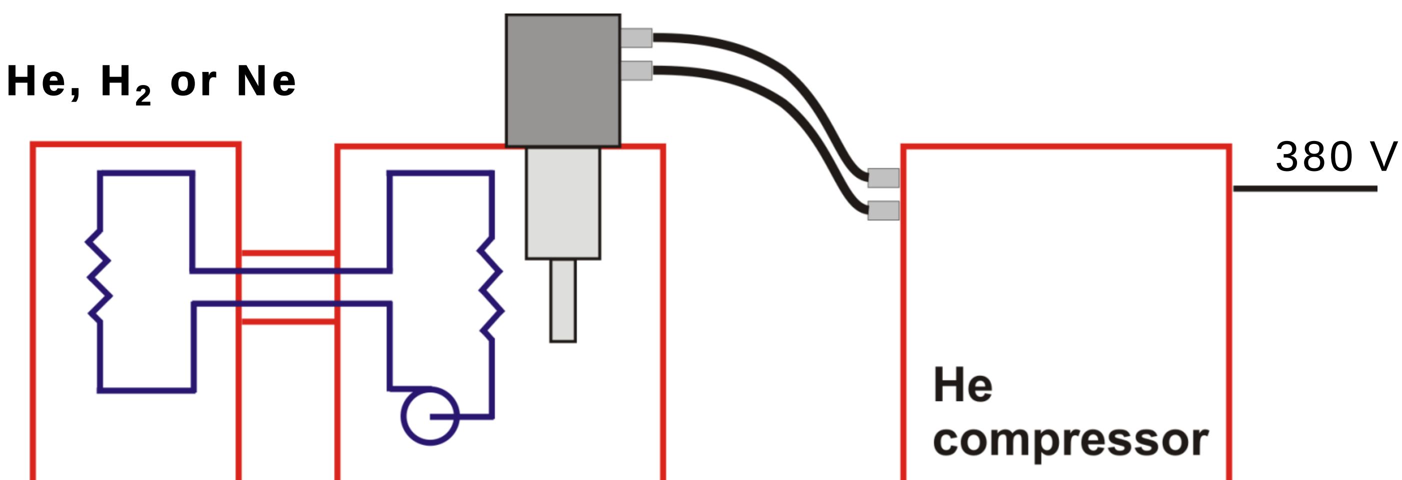
¤Price of small quantities (200 m)
*GE global Research DE-EE0005143

Cryostat & cryocoolers





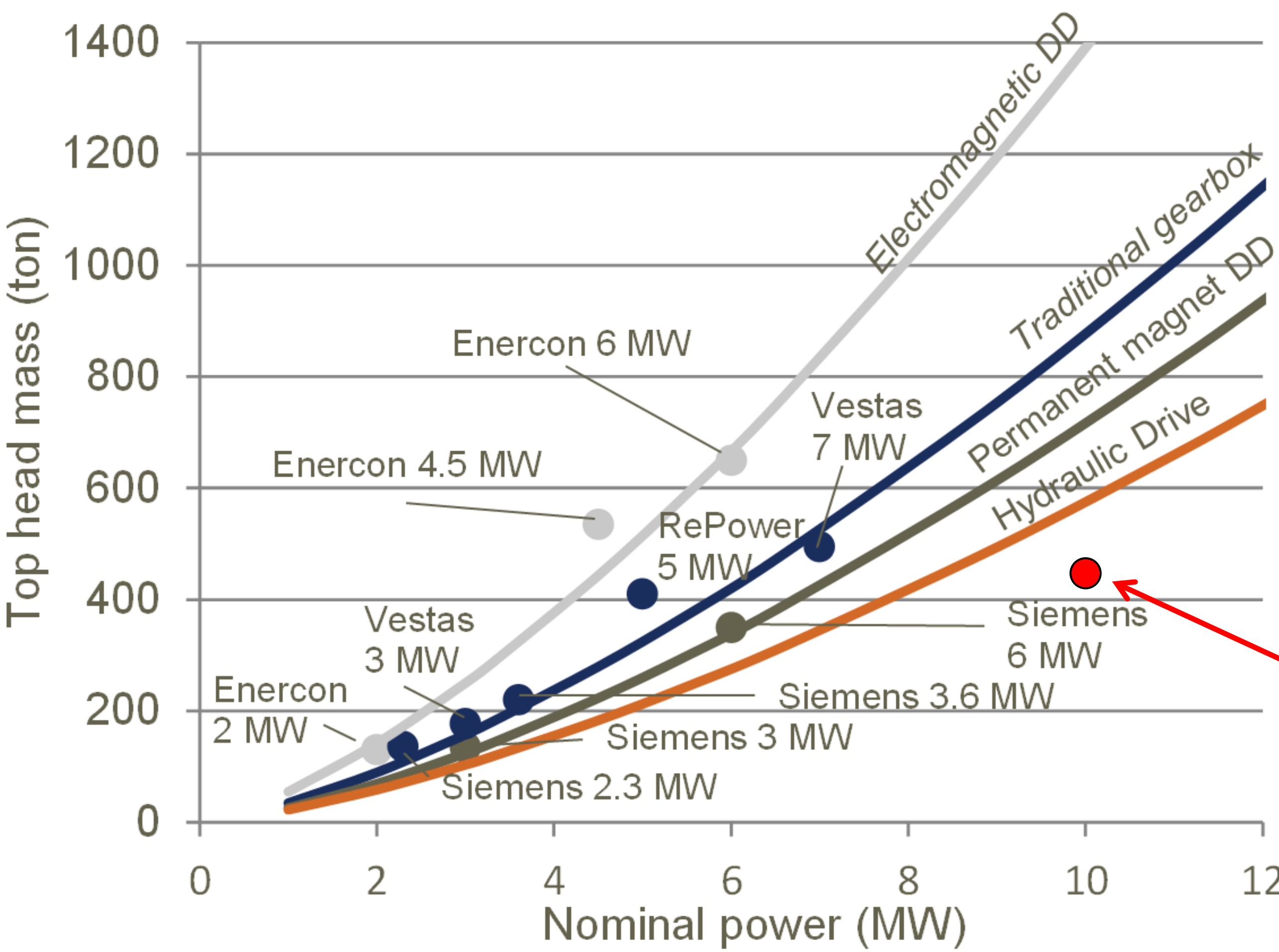
Radebaugh, Proceeding IEEE 92,1719 (2004)



How much of the cooling system can be rotating?

Heat pipes + Cryocoolers

Industrial state of the art
Top head mass (nacelle + rotor)



GE Global Research

- 10 MW DE-EE0005143
- m_{gen} ~142 tons
- D ~ 5 m
- Effic. ~ 90 %
- LTS NbTi wires
- Use of MRI technology
- Cost ~ 280 $/kW
- COE ~ 0.075 $/kWh
- Fixed inner SC coils
- 10MW slip ring

American Superconductors

- 10 MW SeaTitan
- m_{gen} ~ 160 tons
- D ~ 5 m
- $m_{nacelle}$ ~ 420 tons
- Effic. ~ 94 %
- HTS $YBa_2Cu_3O_{6+x}$
- COE ~ ?
- Rotating inner SC coils
- Rotating cold heads

Source: www.btm.dk World market update 2011

Conclusion

Why superconducting?

- A new way of building machines with B_{airgap} higher than saturation of Iron
- B > 1 Tesla $\rightarrow$ More compact for Multi-MW turbines with high torque
- Very small / no dependence on Rare Earth element materials as in PM DD

Cost

• NbTi:	T = 4.2K	Cost ~ 280 $/kW	COE ~ 0.075 $/kWh
• MgB_2:	T = 20 K	Wire up scaling needed	CAPEX % ~4-11
• YBCO:	T = 20-40 K	Wire upscaling & Price reduction	CAPEX % ~40-50

Reliability

- 20000 MRI systems using cryocoolers. Does it transfer to Wind energy?

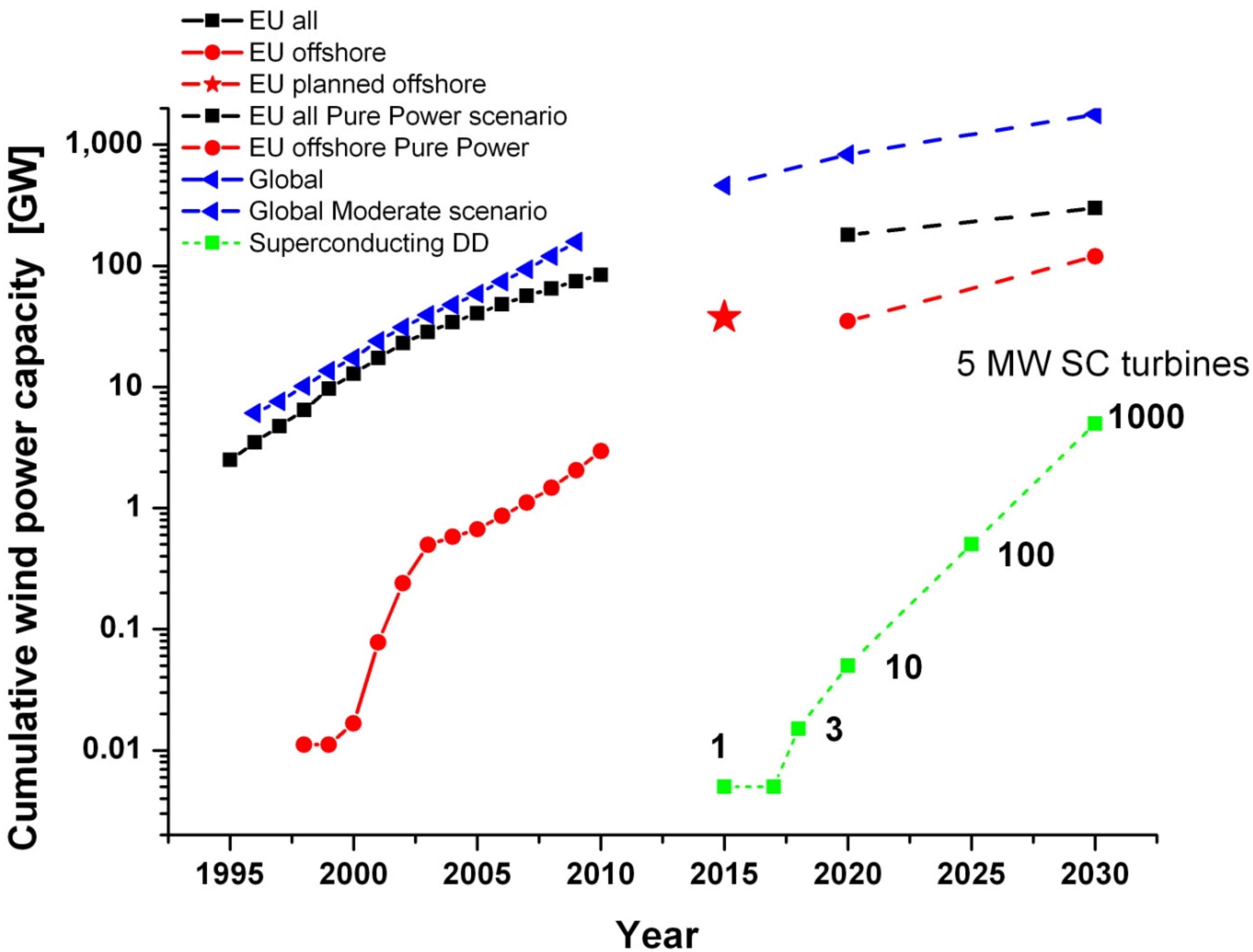
Efficiency

- Similar to permanent magnet direct drive ~ 0.90 - 0.94

Serviceability

- Redundancy of cryocoolers and compressors should provide a service interval of 1 year (MRI). Cold swap of cryocoolers by separate vacuum.

Roadmap to 5 GW SC wind power



YBCO

130000 km tape
3000 km/year ↑ ☹
f_{CAPEX} ~ 40-50% ☹

MgB_2

350000 km tape
5000 km/year ↑ ☹
f_{CAPEX} ~ 4-11% ☺

NbTi

360000 km tape
25000 km/year ☺
f_{CAPEX} ~ 2% ☺

6000 cryocoolers
1000 cryostats

CAPEX << 1/3 ☺
OPEX ? ☹

Abrahamsen and Jensen , "Wind Energy Conversion System: Technology and Trend", ISBN 978-1-4471-2200-5, Springer 2012.